A Desktop Interferometer for Optical Synthesis Imaging

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ABSTRACT

A simple desktop optical interferometer is described and demonstrated as a teaching tool for concepts of long-baseline stellar interferometry. The interferometer is compact, portable, and easily aligned. It sits on a base 8" × 10" and uses an aperture mask which is mounted to rotate within a precision ball-bearing. Fringes produced from an artificial star are observed through a microscope by means of a video camera and are displayed on an overhead television monitor. When the aperture mask is rotated rapidly, the rotating fringe patterns seen on the television are observed to synthesize sources that are unresolved by individual holes in the mask. Fringes from an artificial double star are used to illustrate the relationship between fringe visibility and source structure and to demonstrate image synthesis. The invariance of closure phase is introduced and illustrated. The differences between image synthesis with this interferometer and astronomical interferometers are shown and discusssed.

Keywords: Interferometry, optical, synthesis imaging, teaching

1. INTRODUCTION

This paper describes a small optical interferometer that is useful for teaching concepts of aperture synthesis imaging.

The overall design of the interferometer was developed by Donald Wilson at the University of Cambridge in 1996. In the previous year the Cambridge Optical Aperture Synthesis Telescope (COAST) produced the first optical aperture synthesis images by long-baseline stellar interferometry (Baldwin et al. 1996), and an invitation was extended by the Royal Society for the COAST group to prepare an exhibit for the public at the Royal Society's open-house in London in 1996. The demonstration proved useful for engaging a wide range of audiences at the open house, from the general public to under-graduate and graduate-level students, as well as professional scientists and astronomers. Following the open house, the interferometer was modified and used extensively by John Baldwin in public lectures.

A more compact version of the interferometer, described in this paper, was developed at the Jet Propulsion Laboratory for the Michelson Interferometry Summer School program. The principles and operation of the interferometer are described here.

2. THEORY

The resolution of a convential telescope is ultimately limited by its aperture size. If there are no aberrations, the smallest angular structure that can be resolved is $\sim 1.2\lambda/D$, which is the half-width of an Airy pattern—the distance from the peak of the Airy pattern to the first intensity mininum—and describes the smallest angular separation where two point sources can still be distinguished as separate. However, if two telescopes are used to produce interference fringes, the angular resolution ~~is~~ becomes proportional to the telescope separation, greatly increasing the angular resolution.

A very simple way of illustrating this in the lab is to look at the fringes produced by two small apertures when illuminated by a bright point source and viewed under high magnification through a microscope. The

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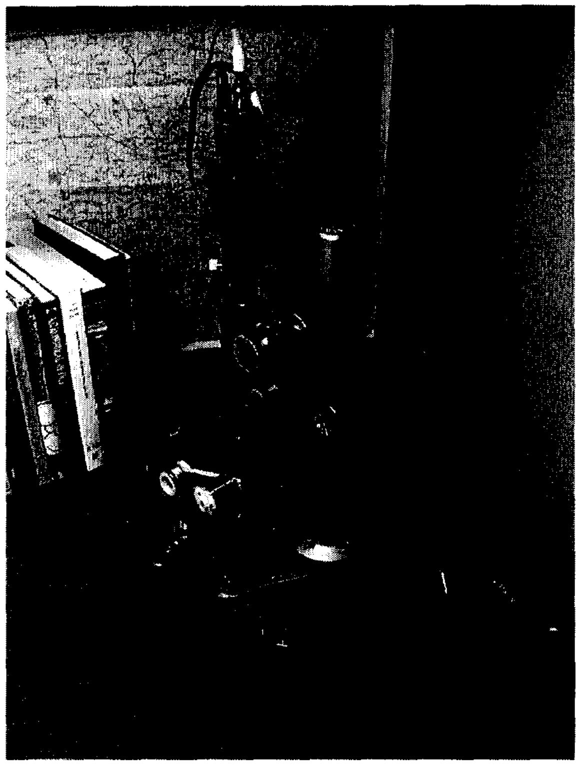


Figure 1. Overview of the tabletop interferometer.

microscope magnifies the diffraction pattern, making the Airy disk and the fringes across it readily visible. It is then straightforward to show that whereas a single aperture can see detail at angular scales comparable to the Airy pattern, the combination of *two* apertures is sensitive to much smaller angular scales, comparable to the fringe width, which can be made arbitrarily small.

To make this point, it is useful to have an artificial star that is a binary source and be able to rotate the source with respect to the two apertures of the interferometer. If the angular separation of the two components of the binary is made to be half a fringe spacing, then as the binary is rotated, the contrast of the fringes will change dramatically. It can be left as an excersize for the audience to determine the orientation of the binary is in its orbit. The correct answer is then immediately obvious when the two small holes are replaced by a single large aperture.

3. APPARATUS

The interferometer contains a telescope with an aperture mask that is mounted so that it can rotate rapidly in a bearing. A small monochrome CCD camera used to display video images of fringes, and other video cameras are used to provide close-up views of the mask and the binary source.

The telescope is folded vertically so that it rests on as compact a base as possible. The base is a 8×10 inch breadboard, 1/2-inch thick, that rests on 1/2-inch legs. An optical beam height of 3 inches above the breadboard was chosen so that standard commercially available optical mounts could be used in the design.

3.1. Aperture Mask

A simple mask with four holes was chosen with a hole size chosen to be $D = 0.8$ mm (1/32 inch). The resolution of the hole is chosen so that the artificial binary star is unresolved. The angular resolution of the hole is $1.2\lambda/D$, so that with an HeNe laser, this corresponds to a separation of 1.5 mm at a distance of 6 ft. The binary star should have components that are much more closely spaced than this if the demonstration is to be impressive.

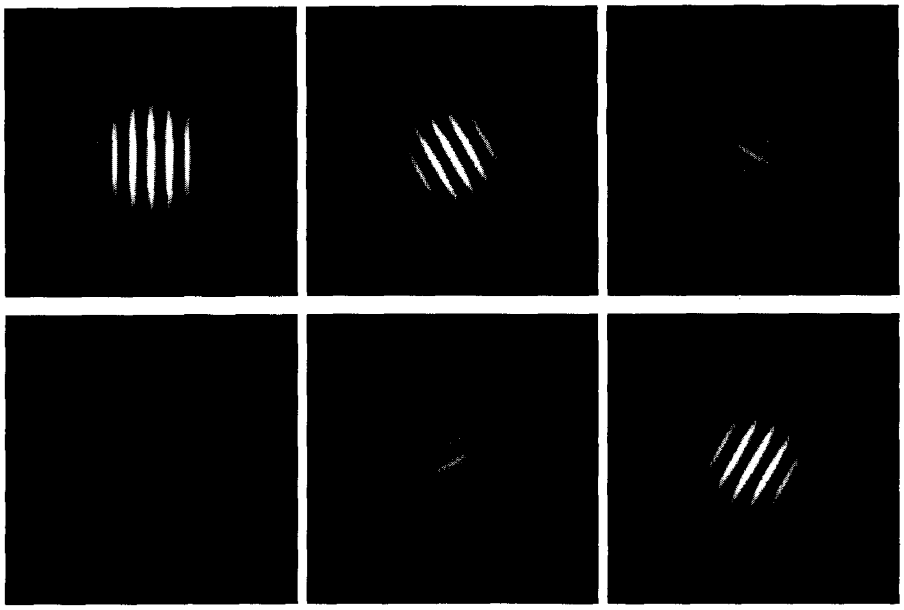


Figure 2. Simulated fringes from a binary star.

This hole size also allows sufficient light through even from a white-light source, such as the filament of a MagLite, and is large enough to be drilled easily. A 4-hole non-redundant square array was used. A number of different arrays are possible, starting with a smallest baseline of $3D$ and extending out to baselines of about 22 mm—slightly smaller than the diameter of the lens immediately after the mask.

The aperture mask was mounted in a bearing so that it could be rotated by a DC motor. A bearing with an outer diameter of 2 inches was chosen to match the diameter of standard optical components, and a flange and mask diameter was then chosen to suit the bearing: the mask was mounted in a nylon flange which in turn was press-fit into the bearing.

3.2. Telescope/Microscope

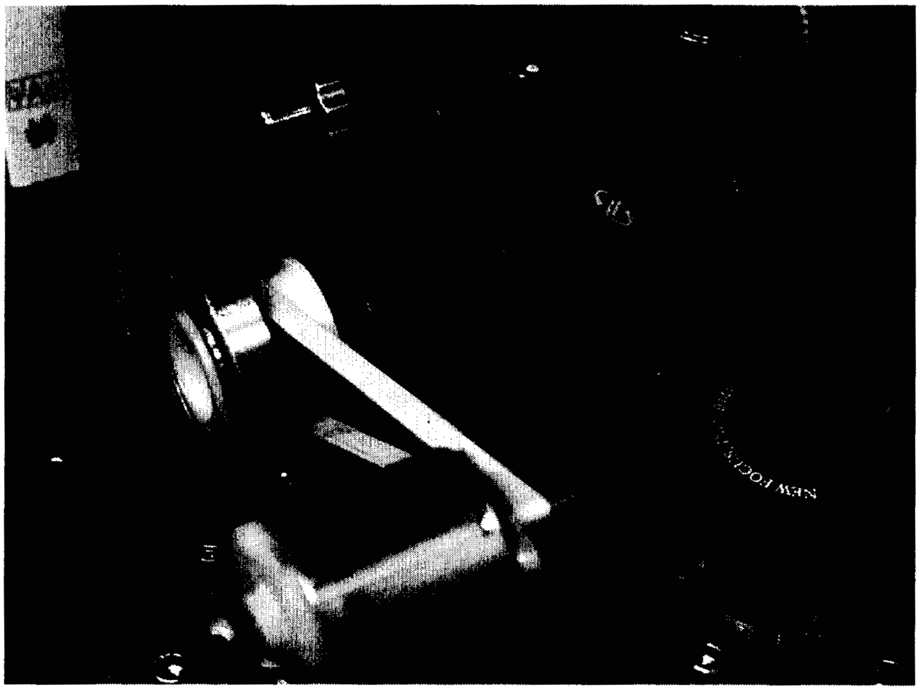
The telescope is built from a microscope and achromatic doublet. The magnification of the telescope is chosen to enlarge the diffraction spot from a hole in the mask, so that the Airy disk almost fills the field-of-view of the CCD camera. A 60× microscope objective, and a $f = 50$ mm, 25-mm diameter, achromatic doublet provides the necessary magnification.

3.3. Artificial Binary Star

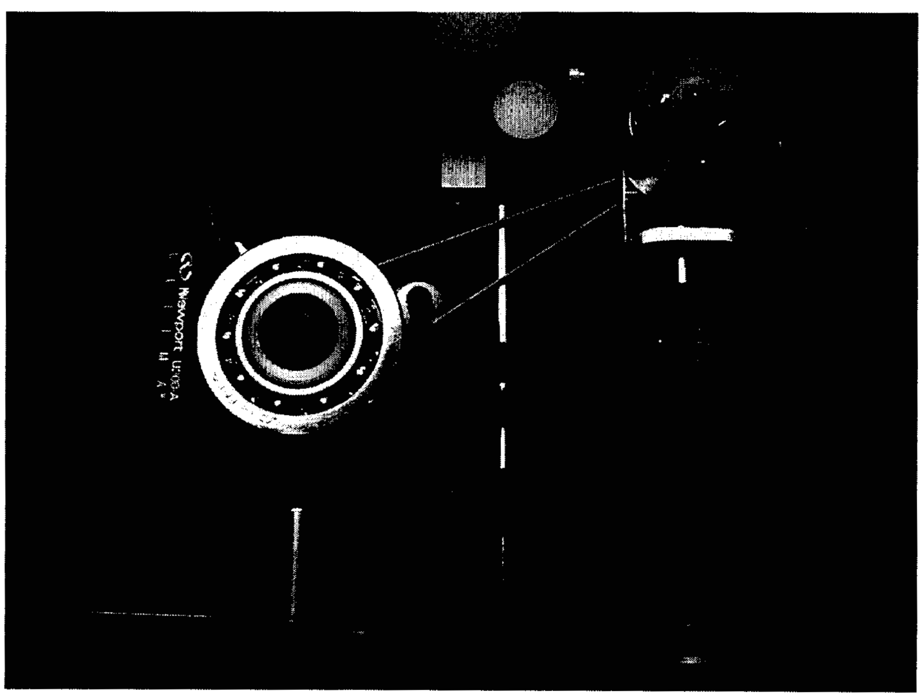
The artificial star was built on the same principle as the aperture mask, but mounted on an adjustable base, which greatly facilitates the alignment.

A small aluminium mask was machined with an outer diameter so that it would press-fit into a nylon flange, which then was pressed into a small bearing. Two small holes, 150 μm in diameter (#97 drill bit), were drilled in the aluminium mask, equally spaced about the center of rotation of the mask, with a center-to-center spacing (between holes) of three hole diameters, or 450 μm. (This is the smallest hole size for which a drill was available.)

The mask is illuminated by a diode laser through a filter wheel carrying an assortment of neutral density filters. The diode laser was chosen to provide a circular beam and be operated with a standard 9-volt battery.



(a)



(b)

Figure 3. View of the mask and dc motor.

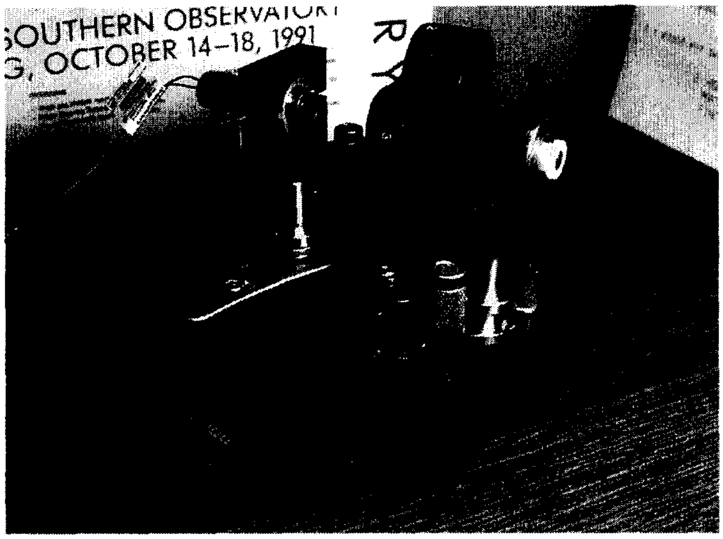


Figure 4. Artificial binary star.

4. PROCEDURE

4.1. Alignment

The alignment takes about 10 minutes. With a small audience it is best to perform the alignment from scratch in their presence, and hand out the parts for them to look while the alignment is in progress. The simplicity of the alignment and the small number of simple components, adds greatly to the overall effect. The steps to the alignment are as follows:

Roughly align the source and the interferometer, placing the two about 6 ft apart. Use a small amount of double-sided tape on the base of each to fix them in place. Check that the pupil of the beam from the source is centered at the height of the mask and unvignetted after reflection by the fold mirror. Adjust as necessary, then remove the mask and all optics, as well as the CCD camera, and put a paper target on the tube where the CCD threads into its mount. Adjust the vertical fold mirror to center the pupil of the beam at the camera. Install the optics, including lens, microscope objective, and CCD camera, but leave out the mask for now. Adjust the x-y position of the lens so that the focused laser beam is centered on the microscope objective. Turn on the CCD camera and view its output on a TV monitor. Defocus the microscope, and adjust the x-y position of the lens until you acquire the (saturated) beam on the monitor. Focus the microscope and re-adjust the x-y position of the lens as necessary to center it. You may need an ND of 3 or 4 to see the Airy rings and a clean focus without saturating the CCD. You should then clearly see the resolved binary. Center the mask in the pupil of the beam; on the video monitor you will then see a complicated fringe pattern that crosses the Airy disk and its first sidelobe. With close inspection you may notice that the Airy disk is not entirely symmetric, because it is slightly elongated in the direction of the binary. The binary is however unresolved.

4.2. Operation

Block all but one of the holes in the mask using common pins. Adjust the ND filters as necessary so that the Airy disk is clearly visible. What is shown is the diffraction pattern of a single hole, and it should be obvious to the students that the resolution in the measurements will be proportional to the width of the Airy disk.

Now unblock a hole for one of the longer baselines. It is obvious that the fringe pattern that appears across the Airy disk now provides sensitivity to angular scales that are much smaller. Rotate the mask and describe the fluctuations in visibility and how that relates to the source geometry.

Now include several other baselines by unblocking all the holes. It is obvious that there is a lot more information available, but it should still appear mostly meaningless to the students. Rotate the mask and show them that the fringe visibility on most baselines changes.

Now attach the elastic band to the motor, and with a great flourish tell the students you are about to synthesize an image an image of the binary star. Turn the motor on and the binary should appear.

5. DISCUSSION

Why does it work so well? Each point source gives rise to its own set of fringes. Each fringe pattern that crosses the Airy disk has a *central* fringe that runs through the angular position of the point source. When the fringes are rotated, they are blurred out everywhere except at the center of rotation, which remains at a constant intensity. The two point sources each provide a different center of rotation for their respective fringe patterns, and thus the sources appear distinct when the mask is rapidly rotated.

If the pupil of the beam in not properly centered on the mask, the intensity of the fringes will fluctuate and the synthesized images will not be as clear, or may degrade or improve when the binary source is rotated.

Note also that it is important to use the appropriate neutral density filters so that the CCD camera does not saturate. If the camera saturates, then background features will become bright enough to distract from the synthesized image of the binary.

6. CONCLUSION

The simplicity of the demonstration allows some fairly sophisticated concepts in synthesis imaging to be illustrated in a very straightforward fashion. The simpler and more hands-on the demonstration can be made, the more accessible it is to the students.

It is of course possible to make the demonstration much more elaborate, by using a video frame grabber and processing the data through software that would be more faithful to astronomical data reduction techniques. It would for example be possible to plot the fringes in the u-v plane, subtract the background, correct for biases in the power spectrum, and thereby produce a cleaner image. It would also be possible to use more complicated masks and to make a more interesting source.

ACKNOWLEDGMENTS

The demo developed at Cambridge University was partly inspired by a demo developed by Michael I. Large at the University of Sydney, which used rotating cylindrical lenses to illustrate the operation of the Mologolo Observatory Synthesis Telescope (MOST). The rapid rotation and relatively slow response of the eye are key the to the success of these demonstrations. Work by PRL was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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